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EFFECT OF LIFT ON SEPARATION DISTANCE AND LOADS FOR AN ABORTING VEHICLE AT MAXIMUM DYNAMIC PRESSURE OF A LUNAR MISSION

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SUMMARY

This investigation considers some of the effects of using lifting trajectories for abort of a lunar mission during the early part of the launch phase. Particular emphasis is placed on determining the effects of lifting abort trajectories on the possibility of a collision of the launch vehicle and spacecraft if abort is initiated at maximum dynamic pressure of the launch trajectory. Abort trajectories are computed with a range of constant values of lift-drag ratio from -1.0 to 1.0 and thrust levels of 83,450 and 151,300 pounds.

The results indicate that a zero-lift abort at maximum dynamic pressure could result in a collision shortly after burnout of the abort motor. However, if the abort vehicle has a lift-drag ratio of ±0.1, positive separation distance from the launch vehicle is maintained. The maximum loads encountered depend somewhat on the lift-drag ratio and are -14.3g for the low thrust level and -18.6g for the high thrust level.

INTRODUCTION

One of the most important aspects of the design of a manned vehicle for any space mission is the provision for aborting the flight safely. In order to insure the safety of the occupants, the capability of executing a successful abort must be available at any time during the flight. The propulsion requirements for abort can, in general, be related to the conditions encountered during the flight. More specifically, there are three important portions of the flight which determine the performance required of the abort propulsion system: (1) off-the-pad abort, (2) abort at maximum dynamic pressure, and (3) postinjection abort at velocities equal to or greater than orbital velocity. Generalized abort studies in the past investigated the problems associated with high abort velocities (14,000 to 30,000 ft/sec) at very high altitudes (250,000 feet and above). (For example, see refs. 1 and 2.)

This paper presents the results of a study of the effects of lift on abort trajectories initiated during the early part of the launch phase of a typical

lunar mission. The major portion of this study deals with the problem of avoiding a collision of the launch vehicle and spacecraft for abort trajectories initiated at flight conditions corresponding to the maximum dynamic pressure expected for the launch of a lunar-type vehicle using the Saturn type propulsion system. A brief consideration of off-the-pad aborts is also included.

At large values of dynamic pressure, the drag-weight ratio of the abort vehicle will be large; once the abort propulsion system burns out, the rapid deceleration of the manned vehicle due to its high drag could result in a collision with the launch vehicle. Thus, it is desirable to investigate the effects of aerodynamic parameters which would make the separation distances of the launch vehicle and spacecraft safe throughout the abort maneuver. In addition, the induced loads on the occupants, due to deceleration at high values of dynamic pressure and acceleration for off-the-pad aborts, must be consistent with acceptable tolerances.

For this study, abort trajectories are calculated for a range of constant values of lift-drag ratio from -1.0 to 1.0. The abort propulsion system assumed has a total impulse at sea level of 200,000 pound-seconds. Two values of thrust for the abort motor are considered: 80,000 and 145,000 pounds (sea-level values) acting for 2.5 and 1.38 seconds, respectively. The trajectory calculations were performed on an IBM 7090 electronic data processing system with a two-degree-of-freedom simulation over a flat earth.

SYMBOLS

A_R	resultant loads imposed on occupant of vehicle, g units
C_D	drag coefficient, $\frac{D}{qS}$
D	drag, lb
Δd	separation distance, ft
g	acceleration due to gravity, 32.17 ft/sec^2
h	altitude above horizontal coordinate axis, ft
L	lift, lb
l	reference length, $r_{ab} + r_{la}$, 101.39 ft
M	Mach number
q	dynamic pressure, lb/sq ft
r_{ab}	radius of abort-vehicle configuration (fig. 4), 16.39 ft

r_{la}	radius of launch-vehicle configuration (fig. 4), 85 ft
S	reference area for abort vehicle, 105.6 sq ft
T	thrust, lb
t	time, sec
V	tangential velocity, ft/sec
W	weight of abort vehicle, lb
x	horizontal distance, ft
α	angle of attack, deg
γ	flight-path angle, deg

Subscripts:

b	refers to burnout of abort motor
ab	refers to abort vehicle
la	refers to launch vehicle

LAUNCH-TRAJECTORY ANALYSIS

Unpublished test results show that aborting conditions such as initial pitch rate, tipoff angles of attack, control-system failure, thrust variation with time, launch-vehicle trajectories, as well as aerodynamics, have significant effects and should be considered in the overall studies of aborting maneuvers. The present study considers only the effects of constant values of L/D for an assumed typical aborting trajectory. The launch trajectory assumed for this study is based on the three-stage version (C-2) of the Saturn system. Figure 1 presents the variation of the flight-path angle and dynamic pressure with time for the first 140 seconds of a representative launch trajectory. For aborts at maximum dynamic pressure the initial conditions selected were: $h = 30{,}000$ feet; $V = 1{,}200$ ft/sec; $\gamma = 70^{\circ}$; and $q = 640$ lb/sq ft. For abort off the launch pad a flight-path angle of 88° was assumed with an initial velocity and altitude of zero.

ABORT-VEHICLE CHARACTERISTICS

The aerodynamic coefficients assumed for the abort vehicle are taken from reference 3. The reference area assumed herein for the abort vehicle is 105.6 square feet. For the purpose of this study, it is assumed that the abort vehicle is statically stable and trimmed throughout the range of flight conditions

covered. The aerodynamic data used in this study are presented in figure 2. Figure 2(a) shows the variation of C_DS with Mach number at zero angle of attack. In order to simplify the calculations, it is assumed that the total drag of the vehicle is the drag at zero angle of attack. The data shown in reference 3 indicate that this results in approximately a 10-percent error in drag at a 10° angle of attack. Figure 2(b) presents the variation of L/D with Mach number at a 10° angle of attack as an illustration of the aerodynamic performance of the vehicle.

The weight and propulsion characteristics assumed for the abort vehicle are presented in table I. It should be noted that, for the abort trajectories initiated at an altitude of 30,000 feet, the motor thrust levels are increased to 83,450 and 151,300 pounds from their respective sea-level values to allow for the reduced ambient pressure at altitude.

The variation of the dynamic pressure with time during abort is presented in figure 3 for the abort thrust levels of 83,450 and 151,300 pounds. The data shown are for abort trajectories with $L/D = 0$. Examination of the trajectory data for the various values of L/D used in this study revealed no significant variation from the dynamic-pressure histories shown in figure 3. It will be noted that the maximum dynamic pressure encountered during the abort trajectories considered herein amounts to 1,105 lb/sq ft and occurs with the thrust level of 151,300 pounds.

CALCULATION PROCEDURE

The abort trajectories computed for this study were planar and were obtained from a two-degree-of-freedom simulation over a flat earth programed for the IBM 7090 electronic data processing system. The 1959 ARDC atmosphere was used for the determination of the density-altitude variation. A flat-earth planar program is employed because this study is concerned with short ranges and relative distances between the abort vehicle and the launch vehicle.

The method of calculating the separation distance Δd between the abort vehicle and the launch vehicle is illustrated schematically in figure 4. For this calculation, it is assumed that both the abort vehicle and the launch vehicle are so oriented that the separation distance is minimized. As shown in figure 4, a negative value of $\Delta d/l$ indicates a possible collision. The equations used in the calculation of the trajectories and the separation distance are presented in the appendix.

RESULTS AND DISCUSSION

Abort at Maximum Dynamic Pressure

Effect of lift-drag ratio on separation distance.- The abort trajectories initiated at $q = 640$ lb/sq ft and $h = 30,000$ feet with a thrust level of 83,450 pounds are shown in figure 5 in the form of altitude-range curves. A

typical thrusting-launch-vehicle trajectory, shown by the dashed curve, is also presented for comparison purposes. The data presented in figure 5 indicate that the range from abort initiation to ground impact is largest for $L/D = \pm 1.0$ and amounts to about 22,000 feet for $L/D = 1.0$ and -15,000 feet for $L/D = -1.0$. It will also be noted that for values of L/D between 0.5 and -0.2 the ground impact points occur between $x = 7{,}000$ feet and $x = 13{,}000$ feet.

The separation distance between the abort vehicle and the launch vehicle is determined from the time history of the abort trajectories shown in figure 6. The separation distance is calculated with the assumption that the launch vehicle is thrusting during the time period covered herein. Figure 6 presents the separation distance Δd, which is normalized by the reference length l, plotted as a function of time for abort trajectories with values of L/D from -1.0 to 1.0. Figures 6(a) and 6(b) present data for the abort-vehicle thrust level of 83,450 pounds; figures 6(c) and 6(d) present data for the abort-vehicle thrust level of 151,300 pounds. Figure 6(a) indicates that collision could occur with a zero-lift abort and 83,450 pounds of thrust at about 1.5 seconds after motor burnout. Increasing the thrust level to 151,300 pounds without increasing the total impulse fails to remedy the situation as indicated by figure 6(c). However, the elapsed time from motor burnout to collision is increased to about 3 seconds with the higher thrust motor. The data presented in figure 6 also indicate that, if the abort vehicle has a value of L/D of ± 0.1, positive separation is maintained throughout the postburnout period. A comparison of figures 6(a) and 6(b) with figures 6(c) and 6(d) shows that, for a given value of L/D, the minimum values of $\Delta d/l$ are somewhat larger for the larger thrust-level aborts.

Examination of the data shown in figures 6(a) and 6(b) shows that after abort motor burnout the minimum values of $\Delta d/l$ are higher for $L/D = 0.1$ and 0.2 than for $L/D = -0.1$ and -0.2. For the $L/D = \pm 0.1$ trajectories, these data show minimum values of $\Delta d/l$ of 0.95 for $L/D = 0.1$, and 0.45 for $L/D = -0.1$. Similarly, for the $L/D = \pm 0.2$ trajectories, the minimum values of $\Delta d/l$ are seen to be 2.3 and 2.15 for $L/D = 0.2$ and -0.2, respectively. A similar comparison can be made with the data shown in figures 6(c) and 6(d) for the abort thrust level of 151,300 pounds. These comparisons indicate that, for the initial abort conditions considered, there is some advantage in using positive rather than negative lift, at least in the range of L/D from -0.2 to 0.2.

Examination of the data shown in figures 6(a) and 6(b) shows that the abort trajectories with $|L/D| > 0.2$ result in continuously increasing separation distances, whereas the trajectories for $|L/D| < 0.2$ show decreasing separation distances shortly after burnout of the propulsion system. From the nature of the data presented, it appears that $|L/D| = 0.2$ is a boundary between trajectories which continuously gain in separation distance and trajectories which lose part of the separation distance provided by the propulsion system. The data presented in figures 6(c) and 6(d) for the thrust level of 151,300 pounds show similar trends; however, with this larger thrust level, it appears that a value of $|L/D|$ between 0.2 and 0.5 is required in order to insure continuously increasing values of separation distance.

Effect of lift-drag ratio on induced loads.- The variation of the resultant loads with time, which would be experienced by the occupants of an abort vehicle for the various abort trajectories discussed previously, is presented in figure 7. The resultant loads are shown for only a few of the trajectories considered in order to show the maximum and minimum values. In general, figure 7 shows that the maximum loads are deceleration loads and occur at burnout of the abort motor. Furthermore, after reaching their peak values, the loads are seen to decrease fairly rapidly with time.

Figure 7(a) presents the resultant loads for abort trajectories having a range of L/D from -1.0 to 1.0 and a thrust level of 83,450 pounds. The peak values of the loads are seen to vary from -9.5g for L/D = 0 to 14.3g for L/D = -1.0. At 3.5 seconds after burnout, the loads have decreased to -1.8g and -4.7g for L/D = 0 and -1.0, respectively.

Figure 7(b) presents the resulting loads for abort trajectories having a range of L/D from -1.0 to 1.0 and a thrust level of 151,300 pounds. The peak values of the loads are seen to vary from -12.5g for L/D = 0 to -18.6g for L/D = -1.0. At 3.5 seconds after burnout, the peak loads have decreased to -2.4g and -5.3g for L/D = 0 and -1.0, respectively.

In figure 8 the maximum positive and negative values of the loads shown in figure 7 are presented as a function of L/D. Data for the abort thrust level of 83,450 pounds are shown by the solid curves and data for the abort thrust level of 151,300 pounds are shown by the dashed curves. The data shown in figure 8 indicate that for relatively small amounts of lift the resultant loads are not significantly different from those obtained with the zero-lift trajectory. For example, an L/D of ±0.3 for either thrust level results in an additional 0.5g deceleration load at burnout of the abort propulsion system.

Abort at Sea Level

Figure 9 presents some altitude-range plots for abort trajectories initiated at sea level with a range of constant values of L/D from -1.0 to 1.0 and an abort thrust level of 80,000 pounds. These data indicate that, for these off-the-pad abort trajectories, the maximum altitude is reached with a range of values of L/D from 0.2 to -0.1 and amounts to about 3,500 feet. The maximum impact range occurs with L/D = 1.0 and is about 2,600 feet.

Figure 10 presents the variation of the resultant loads with time for the constant L/D abort trajectories with abort-thrust levels of 80,000 pounds (fig. 10(a)) and 145,000 pounds (fig. 10(b)). These data indicate that the largest loads occur during the acceleration phase of the abort shortly after ignition of the abort motor. The peak loads amount to 10.4g and 18.8g with thrust levels of 80,000 and 145,000 pounds, respectively. It will also be noted that there is no apparent effect of L/D on the magnitude of the peak loads for the abort trajectories considered herein.

CONCLUDING REMARKS

This investigation has considered some of the effects of utilizing lifting trajectories for abort of a lunar mission during the early part of the launch phase. Two sets of initial abort conditions are considered, those corresponding to the maximum dynamic pressure of the launch trajectory and those corresponding to sea-level conditions.

The results indicate that, for abort initiated at maximum dynamic pressure with a thrust of 83,450 pounds, a zero-lift abort trajectory could result in a collision of the launch vehicle and spacecraft shortly after burnout of the abort motor. Increasing the thrust level to 151,300 pounds, without changing the total impulse, does not alleviate the situation. However, if the abort vehicle has a value of L/D of ±0.1, positive separation from the launch vehicle will be maintained. As would be expected, larger values of L/D, either positive or negative, result in larger separation distances. Indications are that positive values of L/D result in larger separation distances than do negative values of L/D. Also, the larger thrust level results in larger minimum values of separation than does the lower thrust level.

The maximum loads encountered during abort at maximum dynamic pressure are deceleration loads and occur at burnout of the abort motor. The maximum loads increase with increasing absolute values of L/D and with increasing abort thrust; however, negative values of L/D result in slightly larger loads than do positive values of L/D. With an L/D of -1.0, the maximum loads amount to about -14.3g for the thrust level of 83,450 pounds and -18.6g for the thrust level of 151,300 pounds.

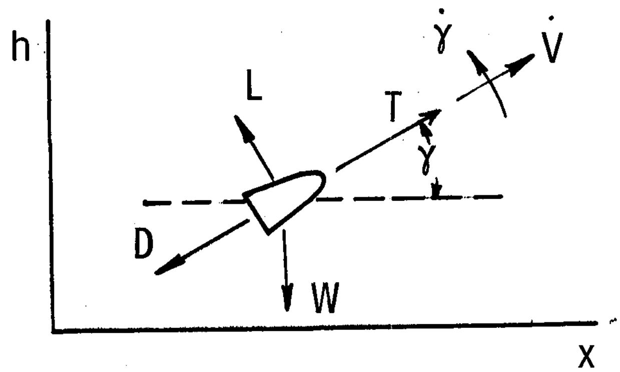
For abort at sea level, the maximum loads occur at ignition of the abort motor. These loads amount to about 10.4g and 18.8g for motor thrust levels of 80,000 pounds and 145,000 pounds, respectively, and are insensitive to the range of L/D investigated.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 25, 1963.

APPENDIX

EQUATIONS USED IN CALCULATION OF ABORT TRAJECTORIES AND SEPARATION DISTANCE

The abort trajectories were computed for trimmed lift-drag ratios with a two-degree-of-freedom computer program over a flat earth. For this study, the direction of the thrust vector is assumed to be alined with the velocity vector. The sketch shown indicates the coordinate system and positive directions of $\dot{V}$ and $V\dot{\gamma}$. The equations of motion in the normal and tangential directions are



$$\dot{V} = \left(\frac{T - C_D S q}{W} - \sin\gamma\right) g$$

$$V\dot{\gamma} = \left(\frac{\frac{L}{D} C_D S q}{W} - \cos\gamma\right) g$$

The total loads sensed by an occupant of the vehicle are found as follows:

$$A_R = \sqrt{\left(\frac{T - C_D S q}{W}\right)^2 + \left(\frac{\frac{L}{D} C_D S q}{W}\right)^2}$$

The sign of A_R is determined by the sign of the first term under the radical of this equation.

With use of figure 4, the separation distance can be determined from the following equation:

$$\Delta d = \sqrt{\left(x_{ab} - x_{la}\right)^2 + \left(h_{ab} - h_{la}\right)^2} - \left(r_{ab} + r_{la}\right)$$

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1. Eggleston, John M., and McGowan, William A.: A Preliminary Study of Some Abort Trajectories Initiated During Launch of a Lunar Mission Vehicle. NASA TM X-530, 1961.

2. Slye, Robert E.: Velocity Requirements for Abort From the Boost Trajectory of a Manned Lunar Mission. NASA TN D-1038, 1961.

3. Brown, Steve W., and Moseley, William C., Jr.: Summary of Wind-Tunnel Investigations of the Static Longitudinal Stability Characteristics of the Production Mercury Configurations at Mach Numbers From 0.05 to 20. NASA TM X-491, 1961.

TABLE I.- CHARACTERISTICS OF VEHICLE AND INITIAL ABORT CONDITIONS

(a) Maximum dynamic pressure

T, lb	83,450	151,300
t_b, sec	2.5	1.38
W, lb	7,744	7,744
W_b, lb	6,910	6,910
γ, deg	70	70
V, ft/sec	1,200	1,200
q, lb/sq ft	640	640
h, ft	30,000	30,000

(b) Sea level

T, lb	80,000	145,000
t_b, sec	2.5	1.38
W, lb	7,744	7,744
W_b, lb	6,910	6,910
γ, deg	88	88
V, ft/sec	0	0
q, lb/sq ft	0	0
h, ft	0	0

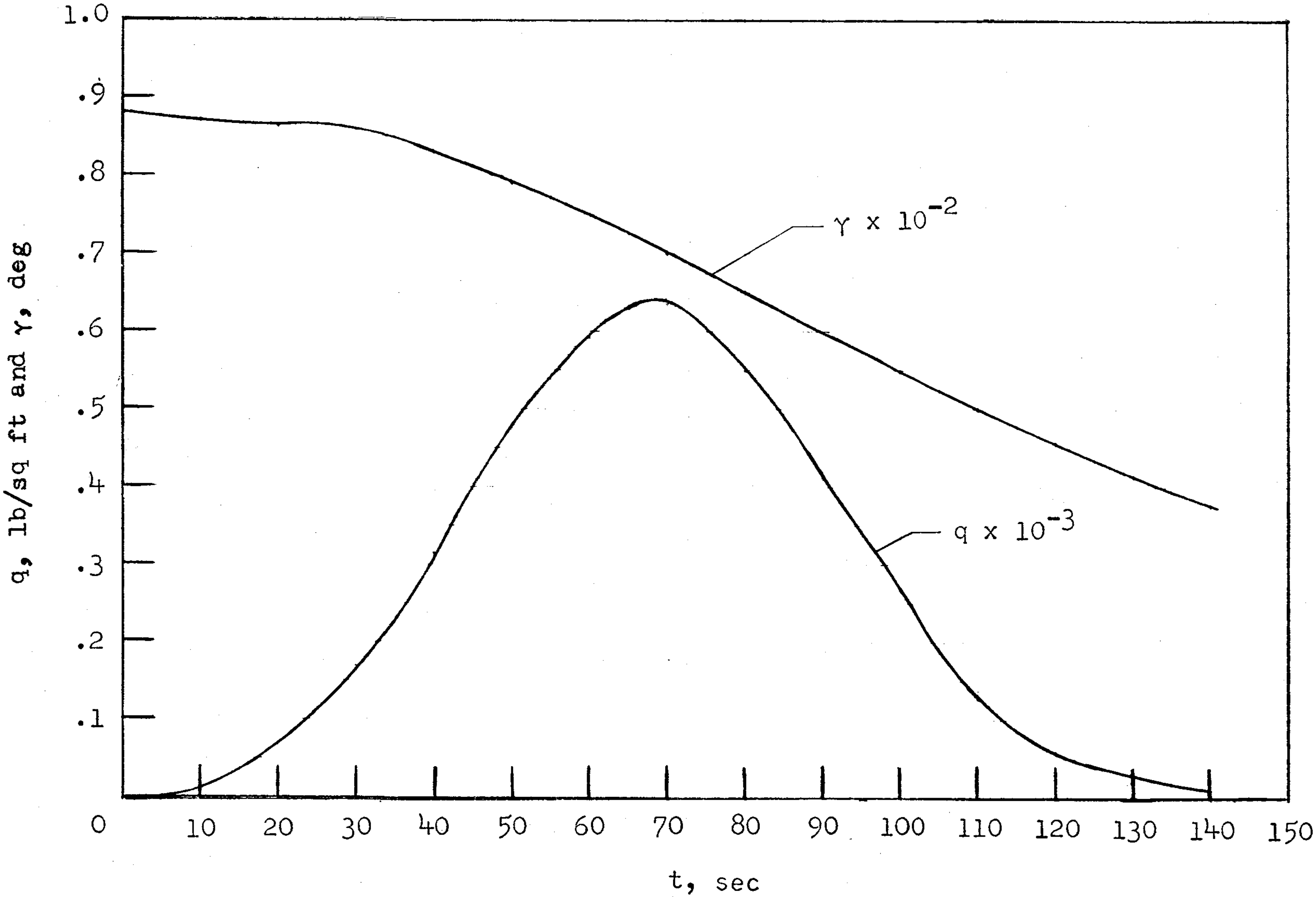
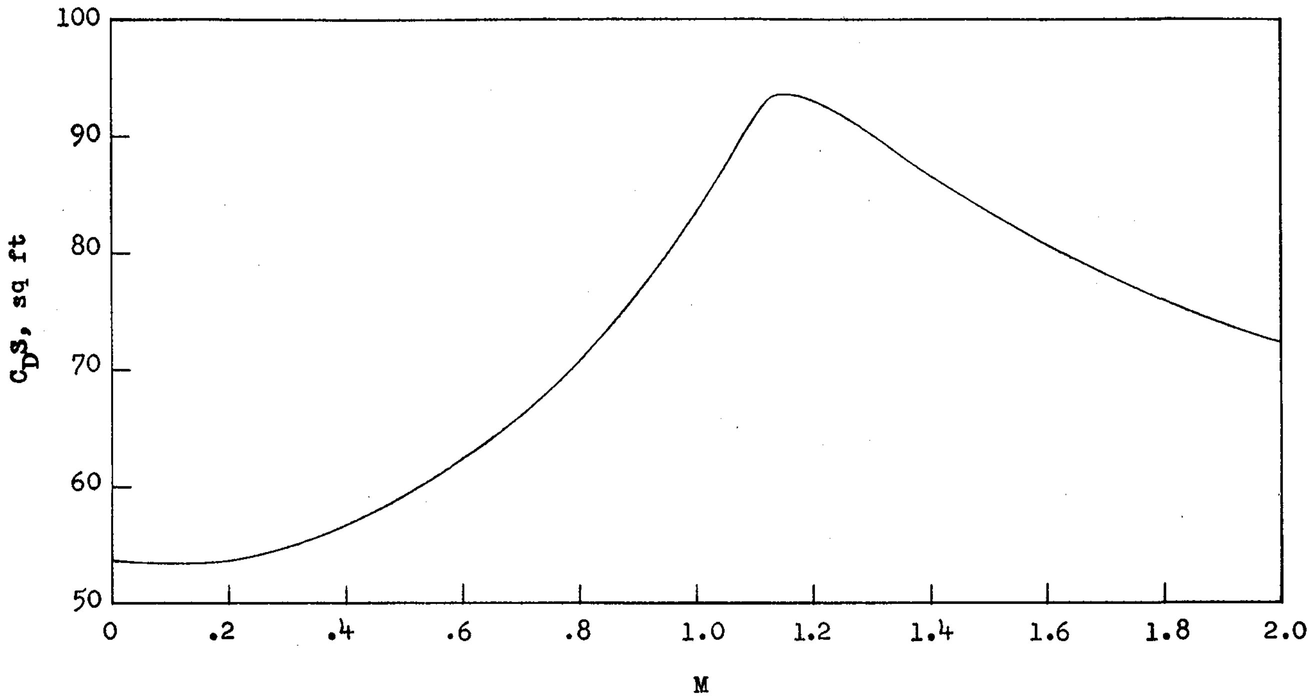
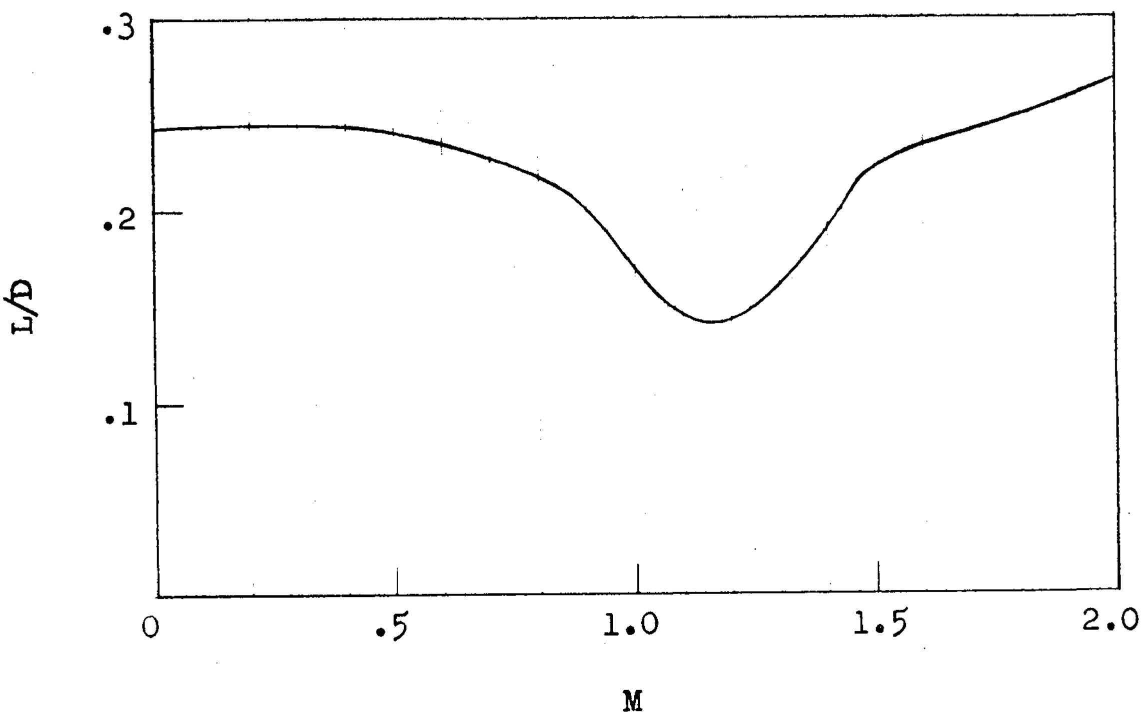


Figure 1.- Characteristics of a representative launch trajectory for an escape mission.



(a) C_DS at $\alpha = 0^{\circ}$.



(b) L/D at $\alpha = 10^{\circ}$.

Figure 2.- Aerodynamic characteristics of abort-vehicle configuration as a function of Mach number.

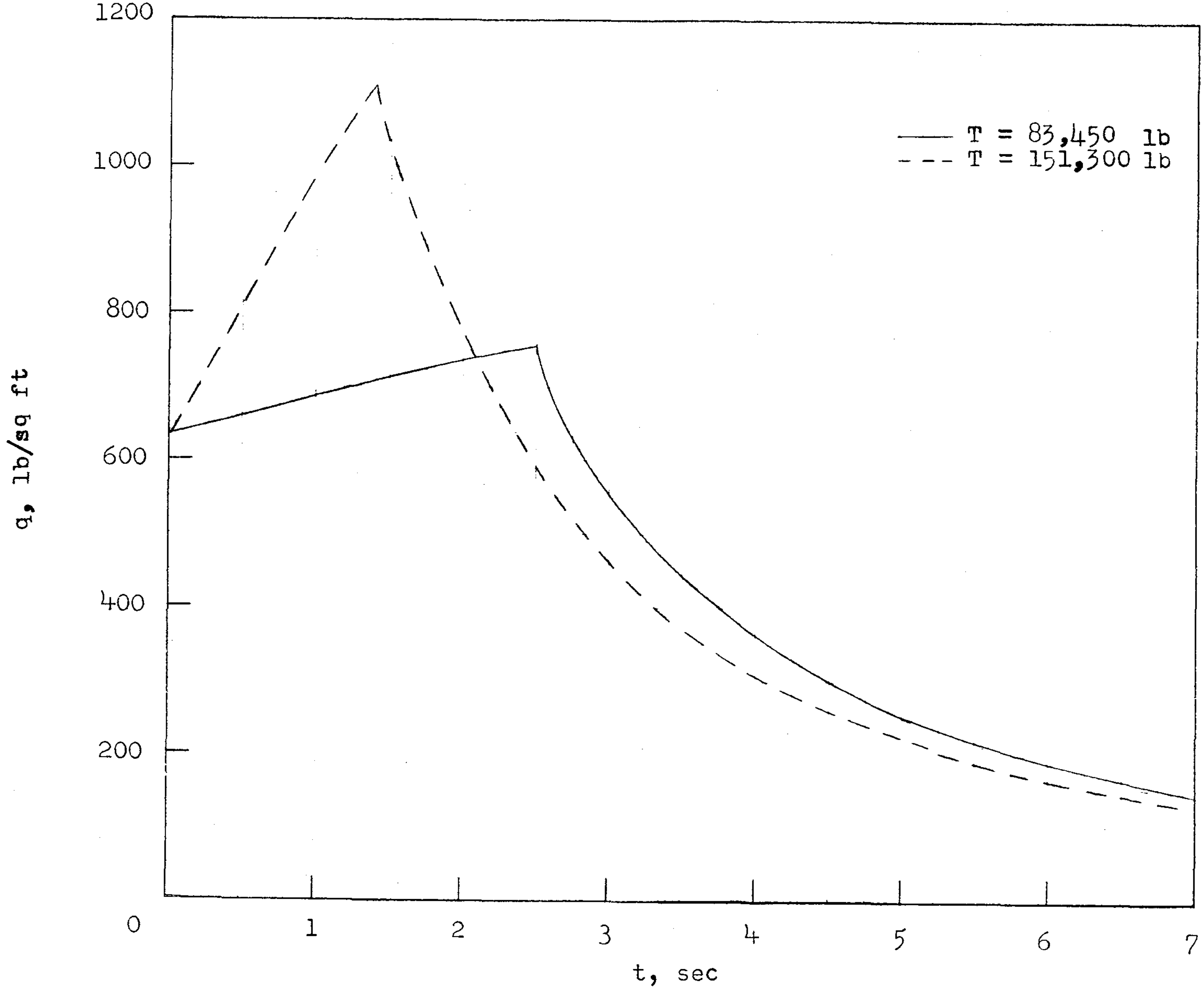


Figure 3.- Dynamic pressure encountered during abort as a function of time.

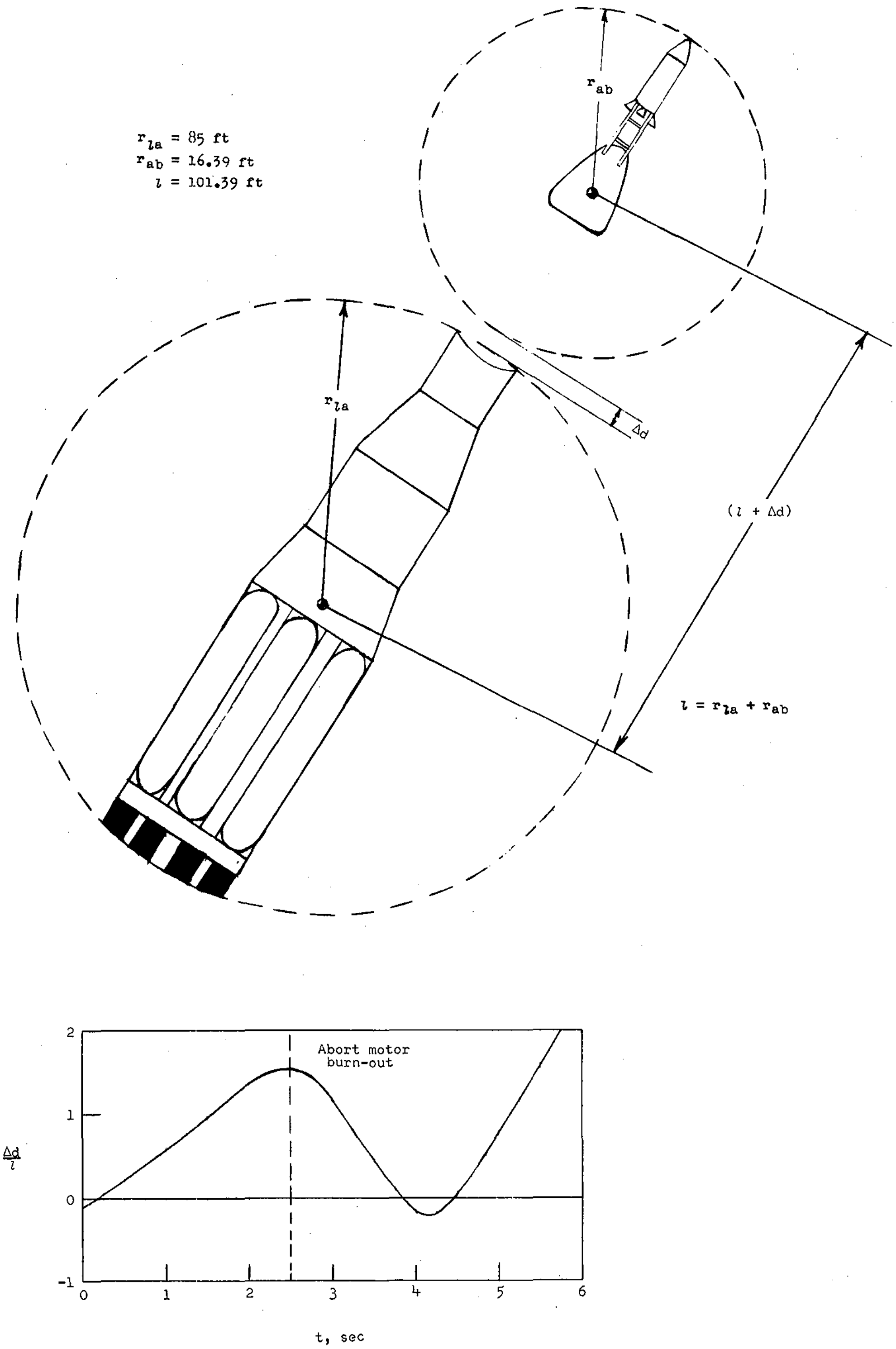


Figure 4.- Schematic illustration of separation distance Δd and a typical variation of $\Delta d/l$ during abort.

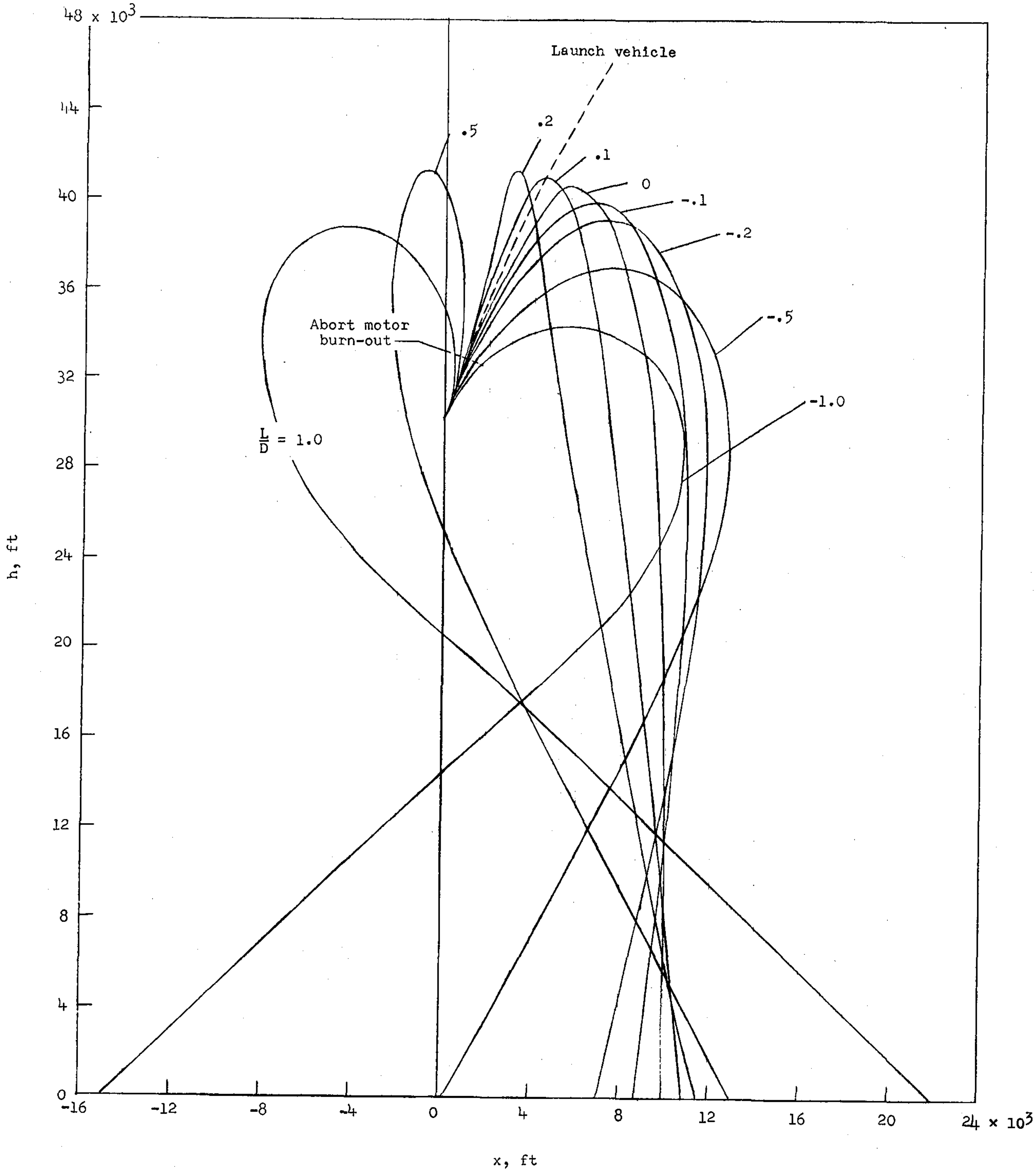
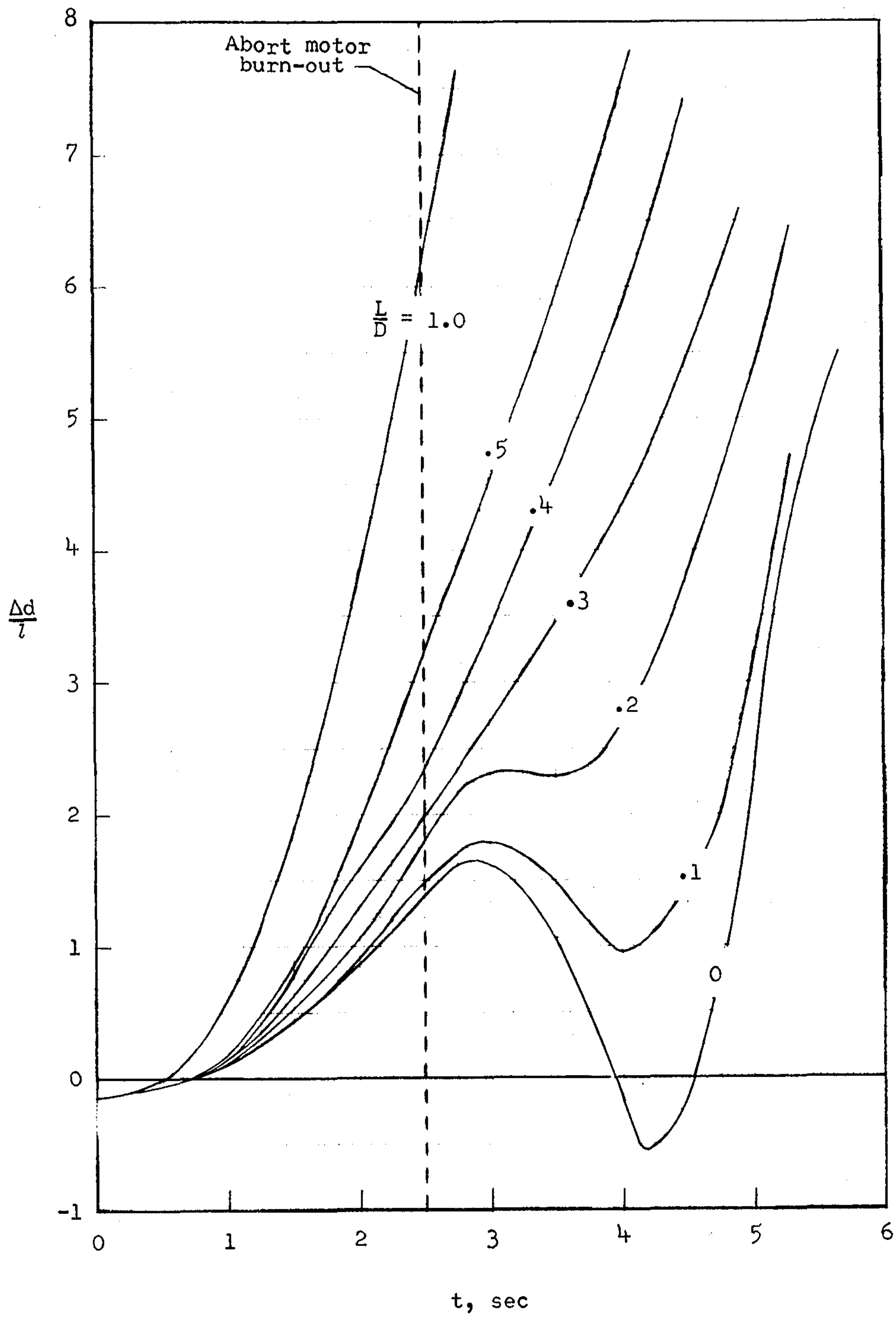
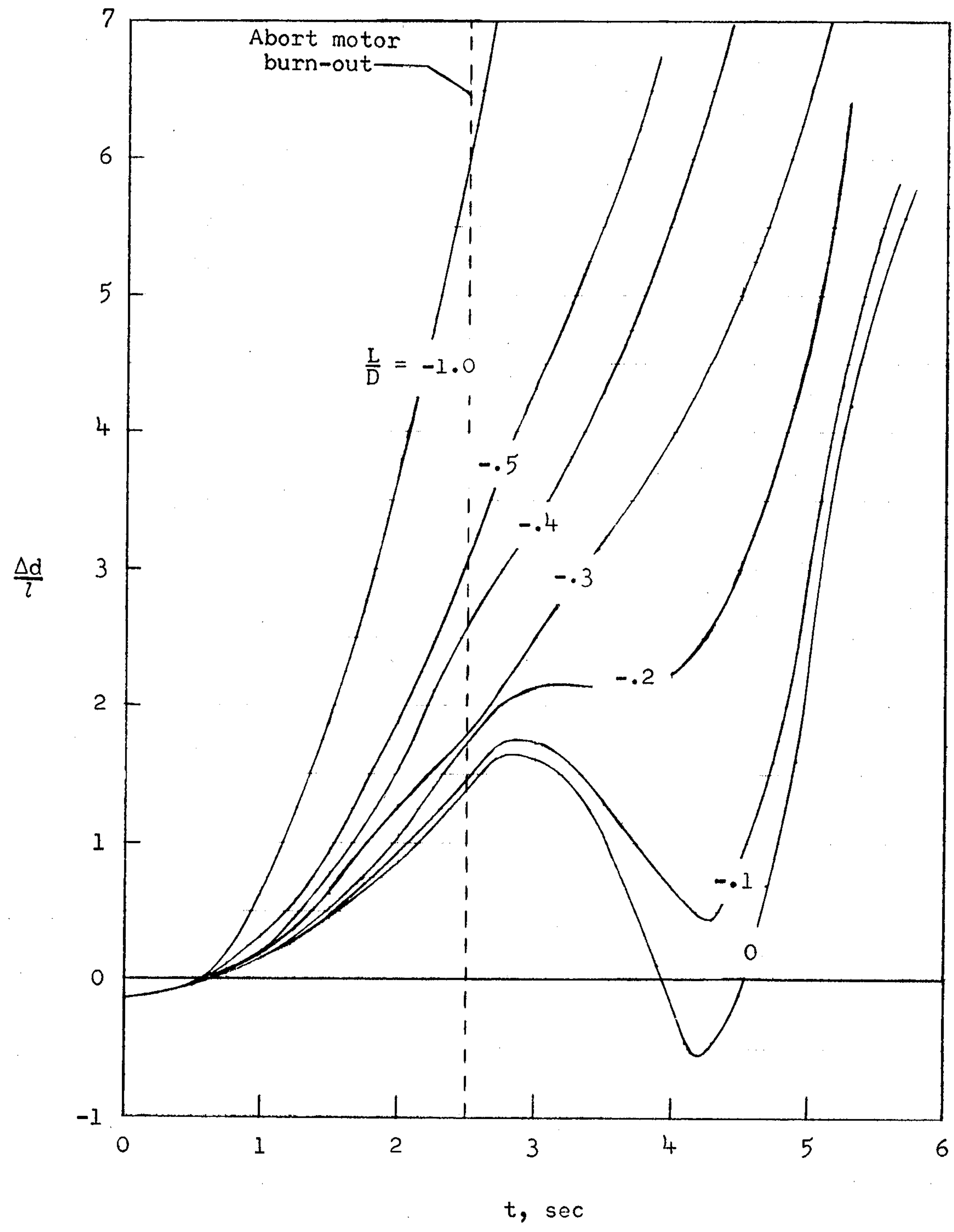


Figure 5.- Constant L/D abort trajectories initiated at $q = 640$ lb/sq ft. $T = 83{,}450$ pounds.



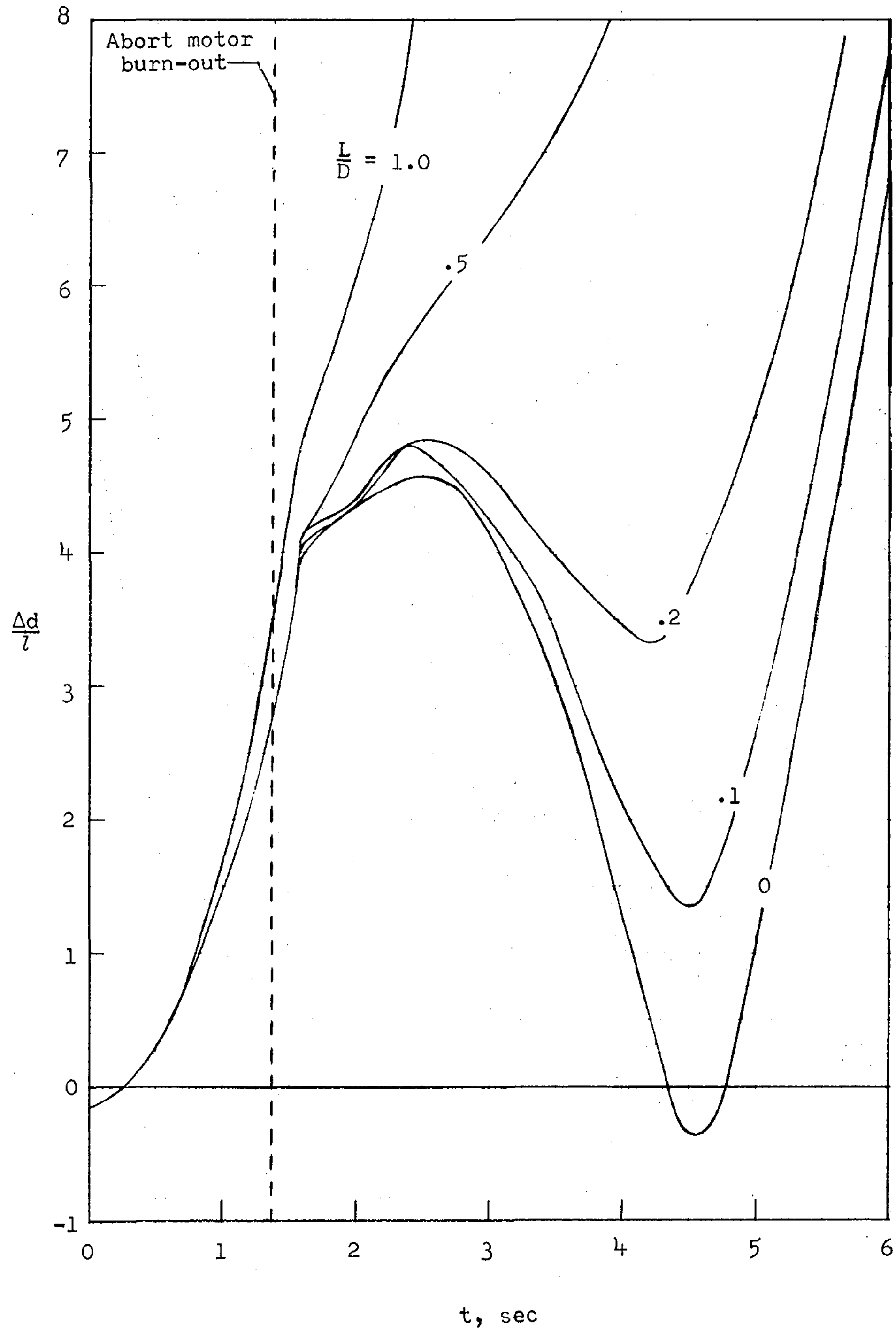
(a) L/D = 0 to 1.0; T = 83,450 pounds.

Figure 6.- Variation of separation distance with time for constant L/D abort trajectories initiated at q = 640 lb/sq ft.



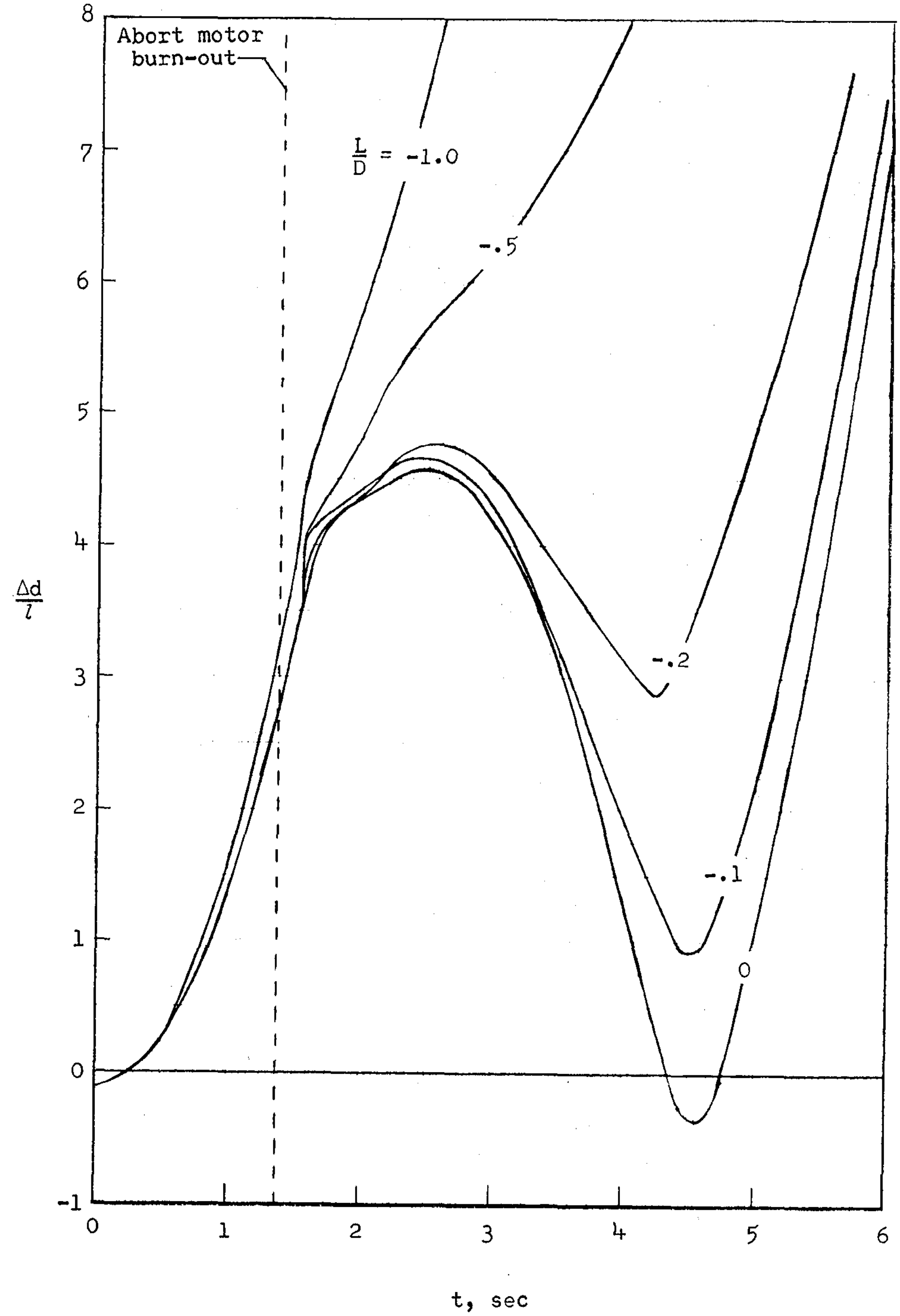
(b) L/D = 0 to -1.0; T = 83,450 pounds.

Figure 6.- Continued.



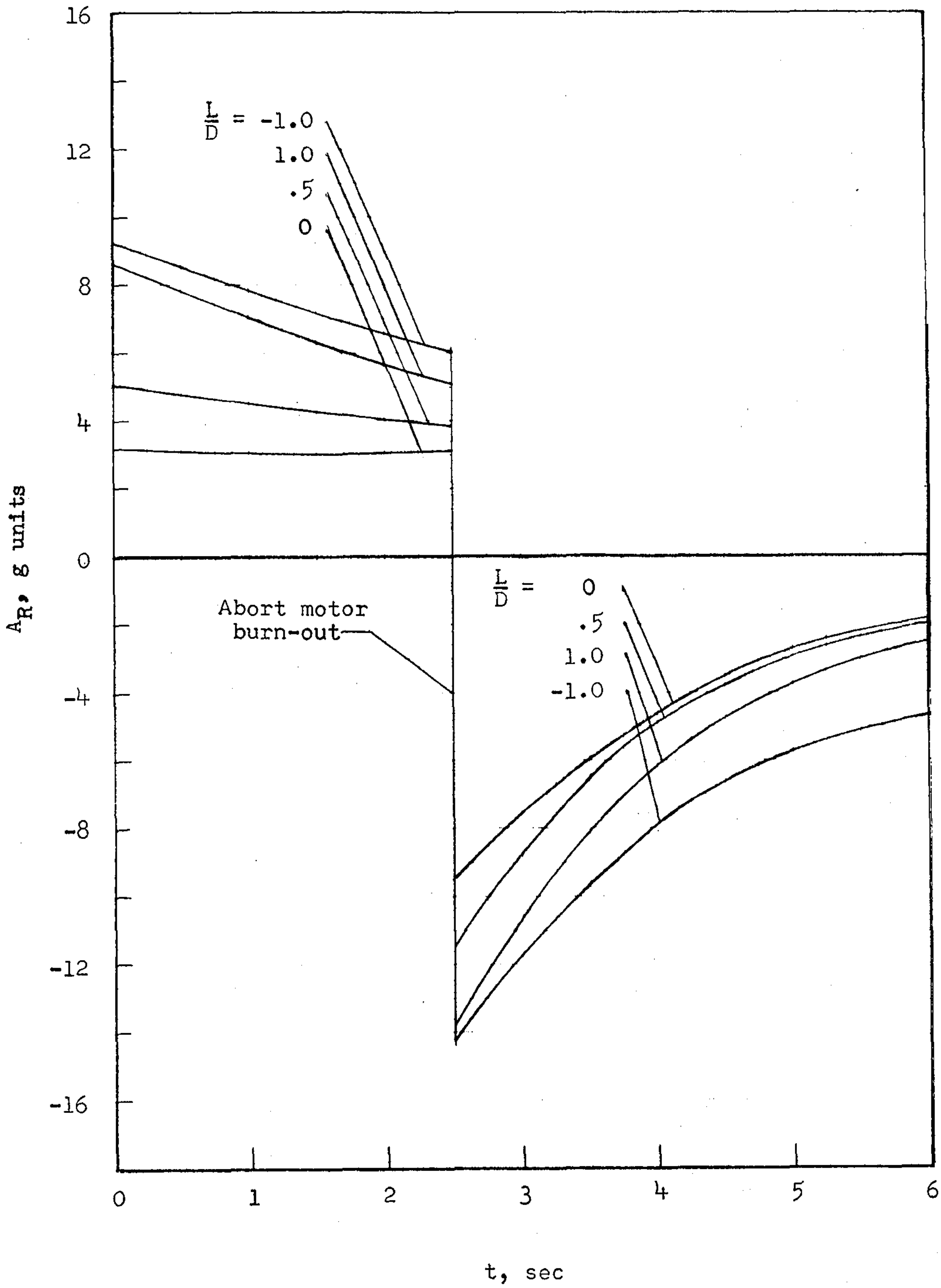
(c) L/D = 0 to 1.0; T = 151,300 pounds.

Figure 6.- Continued.



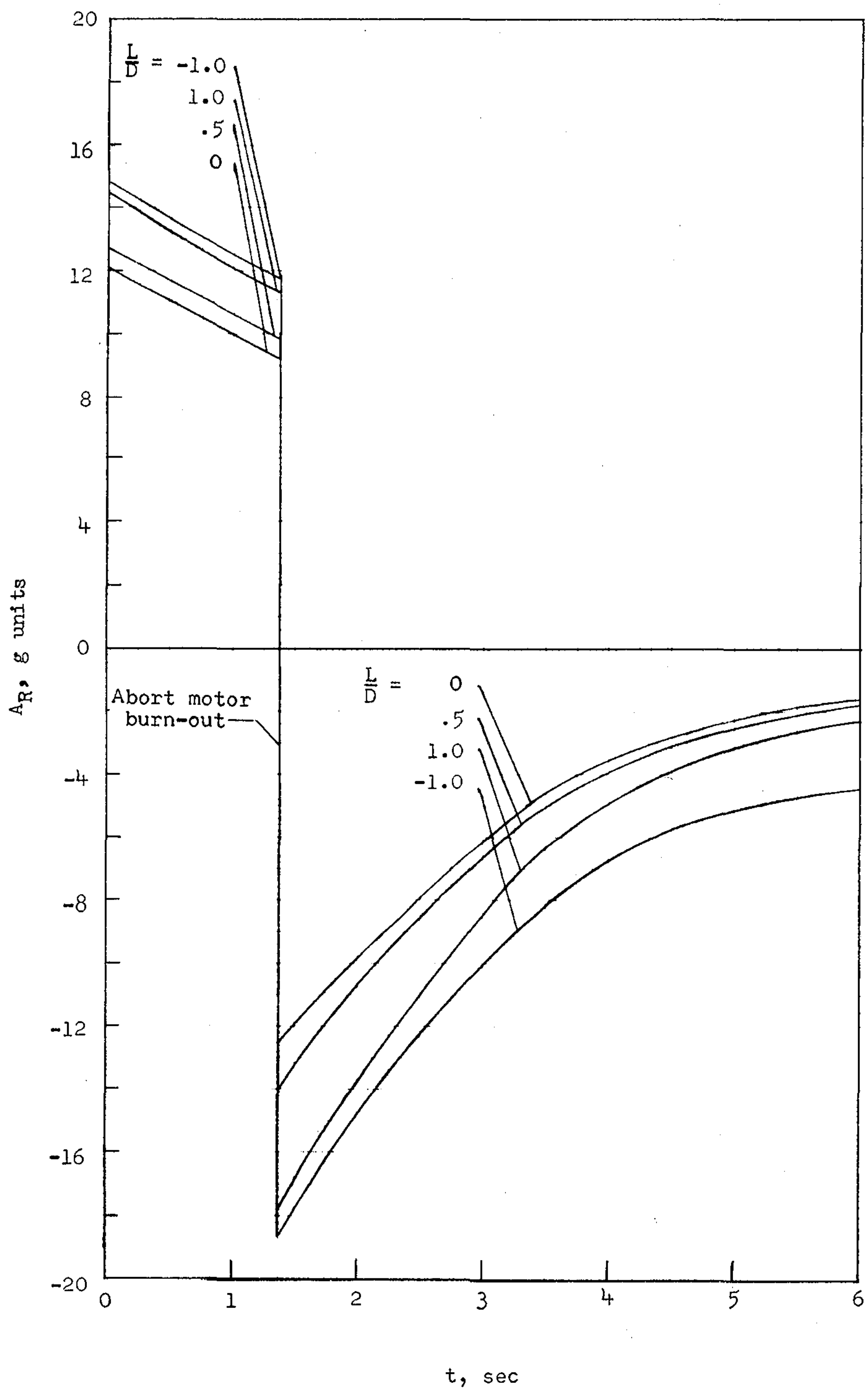
(d) L/D = 0 to -1.0; T = 151,300 pounds.

Figure 6.- Concluded.



(a) T = 83,450 pounds.

Figure 7.- Resultant loads during abort initiated at q = 640 lb/sq ft for a range of values of L/D from -1.0 to 1.0.



(b) T = 151,300 pounds.

Figure 7.- Concluded.

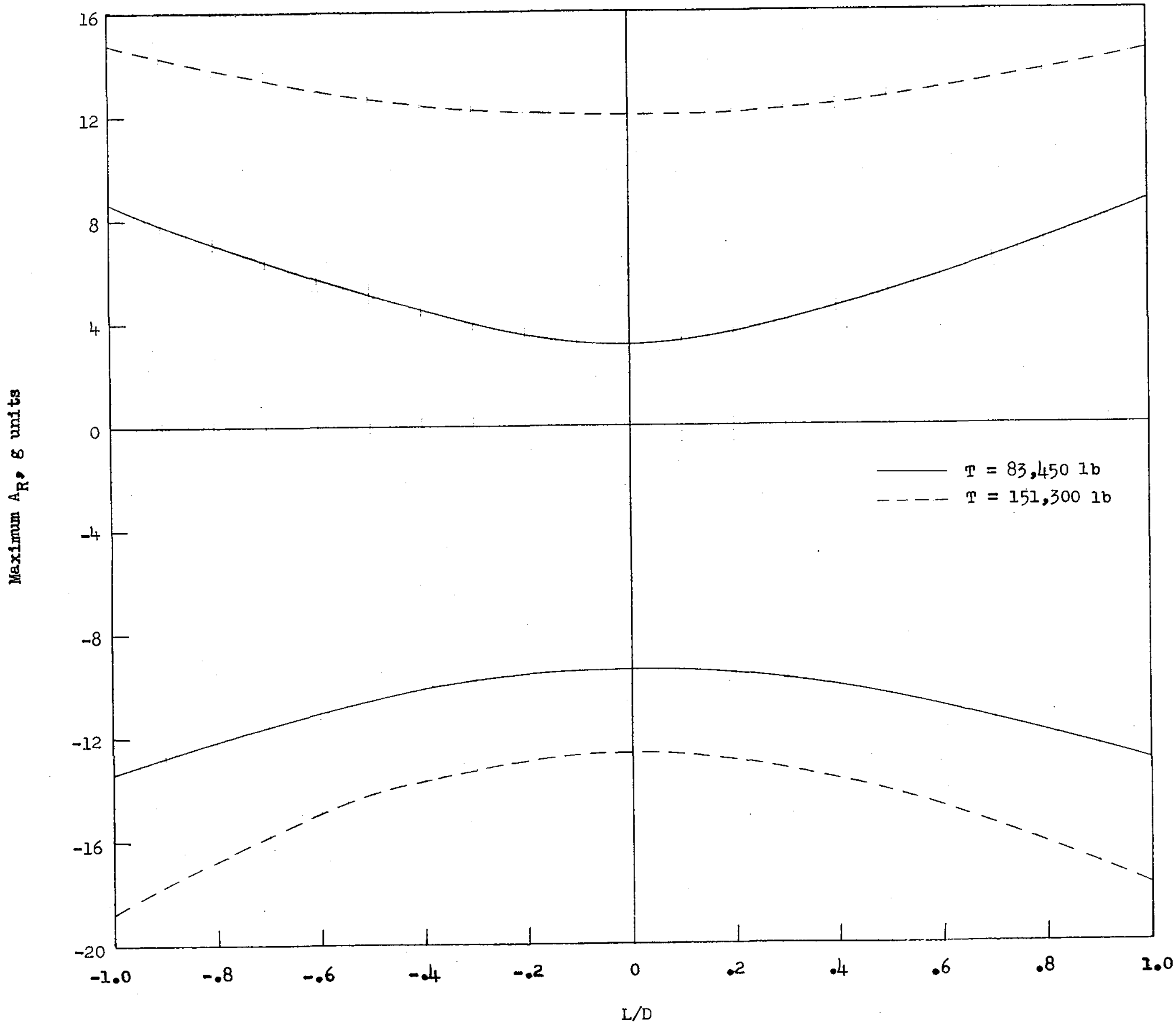


Figure 8.- Effects of L/D on maximum resultant loads during abort at maximum dynamic pressure.

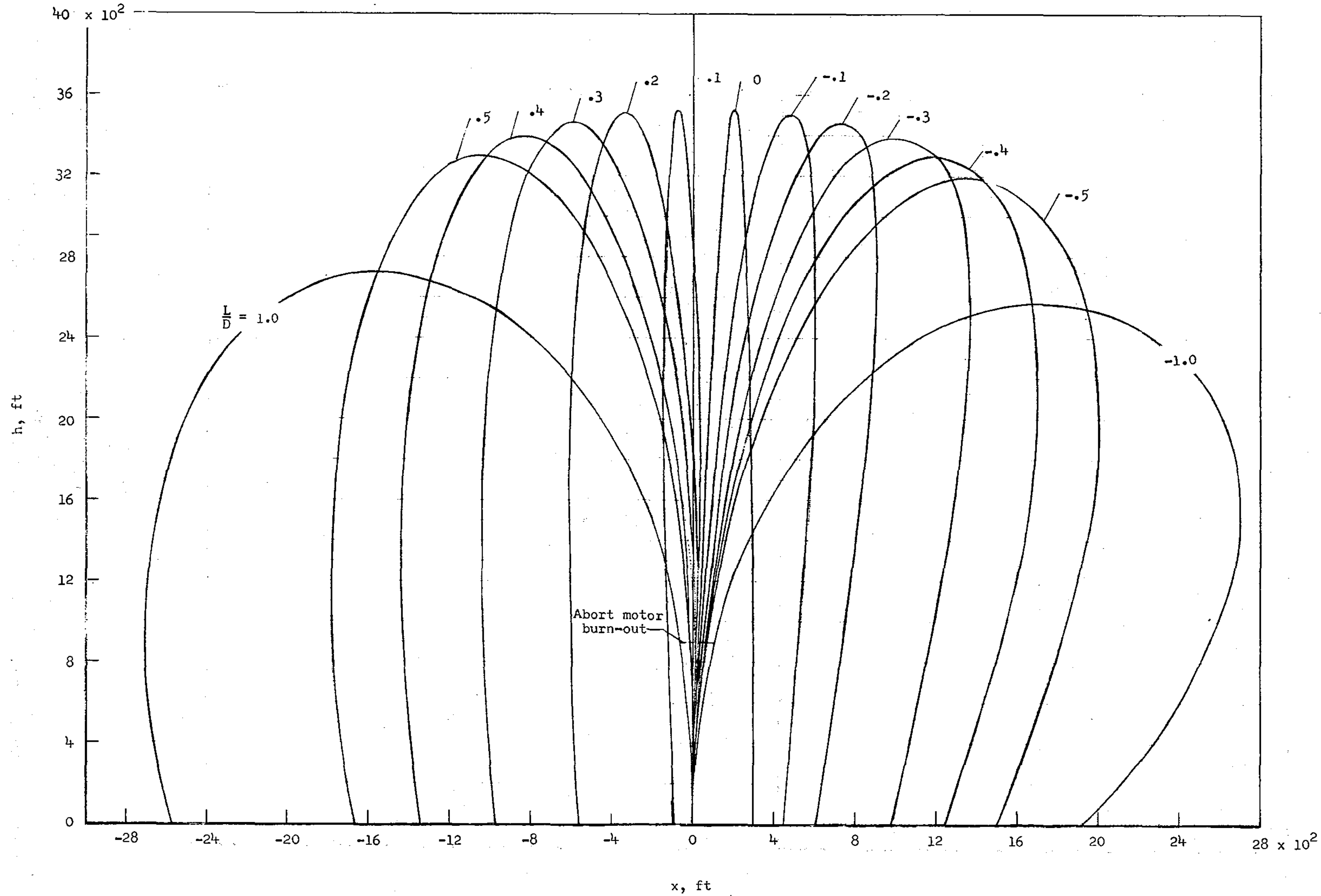
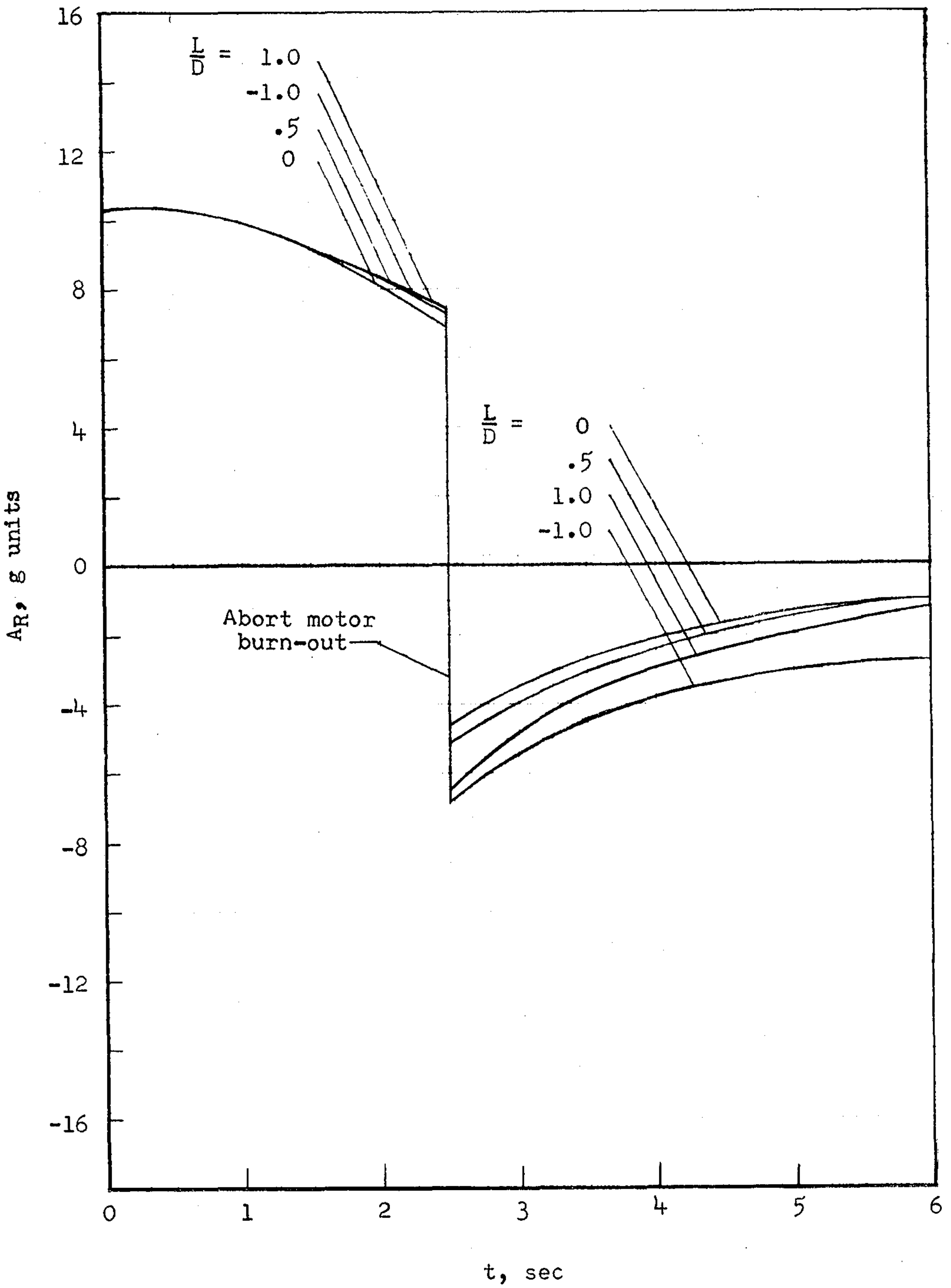
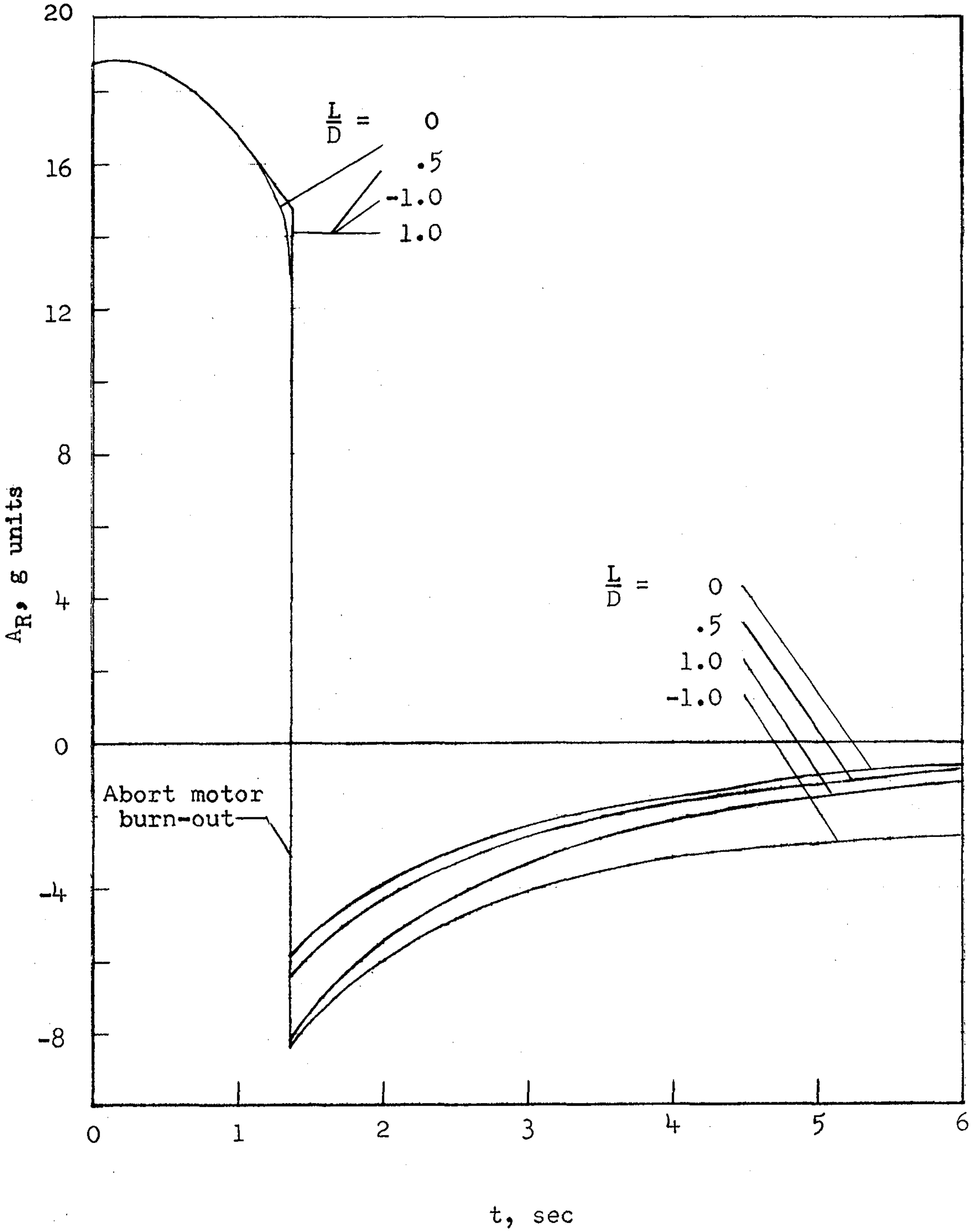


Figure 9.- Abort trajectories initiated at sea level with a range of constant values of L/D. T = 80,000 pounds.



(a) T = 80,000 pounds.

Figure 10.- Variation of resultant loads during abort from sea level for a range of values of L/D from -1.0 to 1.0 and abort thrust levels of 80,000 pounds and 145,000 pounds.



(b) T = 145,000 pounds.

Figure 10.- Concluded.